

Rotational velocities of the giants in symbiotic stars:

I. D'–type symbiotics ^{*}

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ABSTRACT

We have measured the rotational velocities ($v \sin i$) of the mass donors in a number of D'–type symbiotic stars, using the cross-correlation function method. Four from five D' symbiotic stars with known $v \sin i$, appeared to be very fast rotators compared with the catalogues of $v \sin i$ for the corresponding spectral types. At least three of these stars rotate at a substantial fraction ($\gtrsim 0.5$) of the critical velocity. This means that at least in D'–type SS the cool components rotate faster than isolated giants. If these binary stars are synchronized, their orbital periods should be relatively short (4–60 days). We also briefly discuss the possible origin of the rapid rotation and its connection with mass loss and dust formation.

Key words: stars: binaries: symbiotic – stars: rotation – stars: late type

1 INTRODUCTION

The Symbiotic stars (SSs – thought to comprise a white dwarf (WD) accreting from a cool giant or Mira) represent the extremum of the interacting binary star classification. They offer a unique and exciting laboratory in which to study such important processes as (i) mass loss from cool giants and the formation of Planetary Nebulae; (ii) accretion onto compact objects, (iii) photoionisation and radiative transfer in gaseous nebulae, and (iv) nonrelativistic jets and bipolar outflows (i.e. Kenyon 1986; Corradi et al. 2003).

Soker (2002) has shown theoretically that the cool companions in symbiotic systems are likely to rotate much faster than isolated cool giants or those in wide binary systems. However, there are no systematic investigations of $v \sin i$ of the mass donors in SS.

On the basis of their IR properties, SS have been classified into stellar continuum (S) and dusty (D or D') types. The D–type systems contain Mira variables as mass donors. The D'–type are characterized by an earlier spectral type (F–K) of the cool component, and lower dust temperatures.

Among 188 objects in the latest catalogue of symbiotic stars (Belczyński et al. 2000), there are only seven that are classified as D'–type: Wray15–157, AS 201, V417 Cen, HD 330036, AS 269, StH α 190 and Hen 3–1591 (Hen 3–1591 can be S or D'). Three of these have been studied using model atmospheres and all display rapid rotation and s-process elemental over-abundances (see Pereira et al. 2005).

Our aims here are: **(1)** to measure the projected rotational velocities ($v \sin i$) and the rotational periods (P_{rot}) of the giants in D' symbiotic stars, using a cross correlation function (CCF) approach; **(2)** to test the theoretical predictions that the mass donors in SSs are faster rotators than the isolated giants or those in wide binary systems; **(3)** to provide pointers to the determination of binary periods (assuming co-rotation). This is the first of a series of papers exploring the rotation velocities of the mass donating (cool) components of SSs.

2 OBSERVATIONS

The observations were performed with FEROS at the 2.2m telescope (ESO, La Silla). FEROS is a fibre-fed Echelle spectrograph, providing a high resolution of $\lambda/\Delta\lambda = 48000$, a wide wavelength coverage from about 4000 Å to 8000 Å in one exposure and a high overall efficiency (Kaufer et al.

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1999). The 39 orders of the Echelle spectrum are registered on a 2k×4k EEV CCD. All spectra are reduced using the dedicated FEROS data reduction software implemented in the ESO-MIDAS system.

3 $v \sin i$ MEASUREMENT TECHNIQUE

Radial velocities and projected rotational velocities have been derived by cross-correlating the observed spectra with a K0-type numerical mask yielding a cross-correlation function (CCF) whose centre gives the radial velocity and whose width is related to the broadening mechanisms affecting the whole spectra such as stellar rotation and turbulence. Details of the cross-correlation procedure are given in Melo et al. (2001).

In order to use the width (σ) of the CCF as an estimate of $v \sin i$ one needs to subtract the amount of broadening contributing to σ unrelated to stellar rotation (e.g., convection, instrumental profile, etc.), i.e., σ_0 . Melo et al. (2001) calibrated σ_0 as a function of $(B - V)$ for FEROS spectra of stars with $0.6 < (B - V) < 1.2$. The $v \sin i$ measured from our CCFs for a set of standard stars within this $B - V$ range are in good agreement with the literature values. Therefore, for all 4 giants in Table 1, the Melo et al. (2001) calibration has been adopted.

For $v \sin i$ greater than about 30 km s^{-1} the shape of the CCF becomes gradually closer to the Gray rotational profile (Gray 1976). Therefore in order to correctly fit the CCF, a different approach is needed as described in Melo (2003). The CCF is then fitted by a family of functions $CCF_{V \sin i} = C - D[g_0 \otimes G(V \sin i)]$ which is the result of the convolution of the CCF of a non-rotating star g_0 , which can be fairly approximated by a gaussian, and the Gray (Gray 1976) rotational profile computed for several rotational velocities $G(V \sin i)$. For each function $CCF_{V \sin i}$ we found the radial velocity V_r , the depth D and the continuum C for minimizing the quantity $\chi^2_{V \sin i}$ which is the traditional χ^2 function with $\sigma_i = 1$, where σ_i is the measurement error (see Fig. 1 of Melo 2003, for an example of the procedure). The CCFs of our objects are plotted in Fig. 1.

For $v \sin i > 30 \text{ km s}^{-1}$ the typical error of our $v \sin i$ measurements is 10%. For $10 < v \sin i \leq 30 \text{ km s}^{-1}$ the error is about 1.5 km s^{-1} . Our measurements are given in Table 1.

4 ROTATION OF THE MASS DONORS

4.1 Individual objects

HD 330036 : Pereira et al. (2005) obtained $L=650 L_\odot$ for the cool component (with possible uncertainties $160 < L < 3000 L_\odot$), $T_{\text{eff}} = 6200 \pm 150 \text{ K}$, $\log g = 2.4 \pm 0.7$. This imply $R_g = 22 R_\odot$ (using $L = 4\pi\sigma_{\text{SB}} R_g^2 T_{\text{eff}}^4$), $M_g = 4.46 M_\odot$ (using R_g and $\log g$), and $P_{\text{rot}} \lesssim 10.4 \pm 2.4 \text{ d}$ (using $P_{\text{rot}} v \sin i \leq 2\pi R_g$).

Hen 3-1591 : Medina Tanco & Steiner (1995) give spectral type K1 for the cool component. We assume that it is luminosity class III. The average radius of a K1III star is $23.9 \pm 3 R_\odot$ and the average $T_{\text{eff}} = 4280 \pm 200 \text{ K}$ (van Belle et al. 1999). A K1III star would have a mass of $3.9 \pm 0.3 M_\odot$ (Allen 1973). The uncertainties correspond

to ± 0.5 spectral types. This will result in $L=172 L_\odot (\pm 20\%)$ and $P_{\text{rot}} \lesssim 51.0 \pm 11.3 \text{ d}$.

StH α 190 : The cool component is of type G4 III/IV with $T_{\text{eff}} = 5300 \pm 150 \text{ K}$, $\log g = 3.0 \pm 0.5$, and $L=45 L_\odot$ (Smith et al. 2001). This implies $R_g = 7.9 \pm 0.4 R_\odot$ and $P_{\text{rot}} \lesssim 3.8 \pm 1.2 \text{ days}$ (upper limit calculated for $R_g = 8.3 R_\odot$ and $\sin i = 1.0$). The upper limit for P_{rot} is considerably shorter than the supposed orbital periods of 171 d (Munari et al. 2001) or 38 d (Smith et al. 2001).

V417 Cen : Van Winckel et al. (1994) detected a photometric period of 245 days. For the cool component they obtained G9 Ib-II, $\log L/L_\odot = 3.5$, $T_{\text{eff}} = 5000 \text{ K}$, $\log g = 1.5 \pm 0.5$. This implies $R_g = 75 R_\odot$ and $P_{\text{rot}} \lesssim 50.6 \pm 10.2 \text{ days}$. P_{rot} is considerably shorter than the period obtained from photometry. However, the photometric period is not confirmed with radial velocity measurements and we do not know whether this is the orbital period.

AS 201 : Following Pereira et al. (2005), the cool component is of type F9III with $T_{\text{eff}} = 6000 \pm 100 \text{ K}$, $L=700 L_\odot$ (with possible uncertainties $300 < L < 1200 L_\odot$), and $\log g = 2.3 \pm 0.3$. This imply $R_g = 24.5 R_\odot$ and $P_{\text{rot}} \lesssim 49.5 \pm 11.0 \text{ days}$.

4.2 Projected rotational velocities $v \sin i$ - comparison with catalogues

There are no systematic investigations of the rotation of the mass donors in SSs. The rotational velocities of 13 S-type systems listed in Fekel et al. (2003) are between $v \sin i = 3.6 - 10.4 \text{ km s}^{-1}$. All D'-type systems so far observed (see Table 2) rotate with $v \sin i > 20 \text{ km s}^{-1}$.

The catalog of de Medeiros et al. (2002) of $v \sin i$ of Ib supergiant stars contains 16 objects from spectral type G8-K0 Ib-II. All they have $v \sin i$ in the range $1-20 \text{ km s}^{-1}$. It means that V417 Cen is an extreme case of very fast rotation for this spectral class.

The catalogue of rotational velocities for evolved stars (de Medeiros et al. 1999) lists ~ 100 K1III stars, and 90% of them rotate with $v \sin i < 8 \text{ km s}^{-1}$. There are only 5 with $v \sin i > 20 \text{ km s}^{-1}$. This means that Hen 3-1591 is a very fast rotator (in the top 5%). The same catalog contains 5 objects from spectral type F8III-F9III. They rotate with $v \sin i$ of $10-35 \text{ km s}^{-1}$. AS 201 is well within in this range. However HD 330036 is an extremely fast rotator. The same catalog lists 60 objects from spectral type G3,G4,G5 III-IV. They all rotate with $v \sin i < 24 \text{ km s}^{-1}$. Again, this means that StH α 190 is an extremely fast rotator.

Thus overall, 4 out of 5 D'-type SSs in our survey are very fast rotators.

4.3 Critical speed of rotation

There is a natural upper limit for rotation speeds, where the centripetal acceleration balances that due to gravitational attraction, often named the "critical speed", where $v_{\text{crit}} = \sqrt{GM/1.5R} = 357 \sqrt{M/R} \text{ km s}^{-1}$ (the factor of 1.5 appears from the assumption that at critical rotation speeds the equatorial radius is 1.5 times the polar radius, R). The calculated v_{crit} is included in Table 2. No star can rotate faster than its critical speed, however we can see that at least three D'-type SSs are rotating at a substantial fraction

Table 1. Journal of observations and projected rotational velocities of D' type SSs (note that value for AS 201 is from the literature). The spectral types of the giants are from different papers (see Section 4.1), (B-V)₀ is the intrinsic colour for the corresponding spectral type. $v \sin i$ is the rotational velocity measured in this paper. The last column gives other measurements of $v \sin i$ (if available).

object	date-obs	MJD	Exp. time	Cool Star Spectrum	(B-V) ₀	$v \sin i$ [km s ⁻¹]	other [km s ⁻¹]
HD 330036	2004-05-22	53147.212	2×10 min	F8III	0.90	107.0±10	100±10 ^a
Hen 3-1591	2004-07-19	53205.222	2×20 min	K1III	1.09	23.71±1.5	
StHα 190	2004-06-03	53159.397	2×10 min	G4III/IV	0.88	105.0±10	100±10 ^b
V417 Cen	2004-04-14	53109.280	2×10 min	G9Ib-II	0.98	75.0±7.5	
AS 201	F9III	0.58	25±5 ^a

^aPereira et al.(2005); ^bSmith et al.(2001);

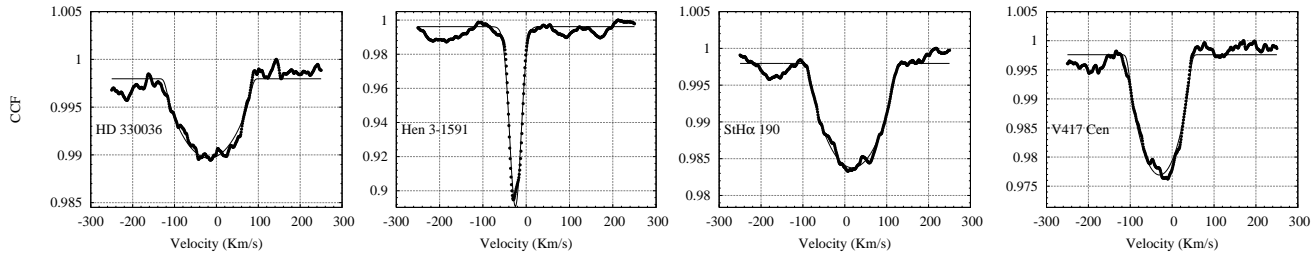


Figure 1. CCF relative intensity (heavy line) and the fit versus radial velocity for SSs observed in this paper.

of their critical speeds: $\frac{v \sin i}{v_{\text{crit}}} \sim 0.67$ (HD 330036), ~ 0.54 (StHα 190), ~ 0.71 (V417 Cen). Probably for these three SSs the orbital inclination is high $i \geq 50^\circ$. For the remaining two objects we can not exclude the possibility that they also rotate very fast but are observed at low inclination ($i \lesssim 30^\circ$).

5 SYNCHRONIZATION AND BINARY PERIODS

5.1 Synchronization in SS

The physics of tidal synchronization for stars with convective envelopes has been analyzed several times (e.g. Zahn 1977 and also the discussion in Chapter 8 of Tassoul 2000). There are some differences in the analysis of different authors, leading to varying synchronization time-scales. Here, we use the estimate from Zahn (1977, 1989): the synchronization time-scale in terms of the period is

$$\tau_{\text{syn}} \approx 800 \left(\frac{M_g R_g}{L_g} \right)^{1/3} \frac{M_g^2 \left(\frac{M_g}{M_{WD}} + 1 \right)^2}{R_g^6} P_{\text{orb}}^4 \text{ years} \quad (1)$$

where M_g and M_{WD} are the masses of the giant and white dwarf respectively, and R_g and L_g are the radius and luminosity of the giant (all in Solar units). The orbital period P is measured in days.

The S-type SSs are very likely synchronized (Schild et al. 2001; Schmutz et al. 1994). Other proof of this supposition is that most of the SSs with derived orbital parameters (see Mikołajewska 2003) have orbital eccentricity $e \approx 0$. Because the circularization time of the orbits is ~ 10 times longer than the synchronization time (Schmutz et al. 1994 and the references therein), if a SS's orbit is circularized it will very likely be synchronized too.

A typical D'-type SS would have $R_g \sim 20R_\odot$, $L_g \sim 500L_\odot$, $M_g \sim 3M_\odot$, and white dwarf mass $M_{WD} \sim 1M_\odot$. For a period of 100 days for a typical D'-type SS, we find $\tau_{\text{syn}} \sim 9 \times 10^4$ years.

For the individual systems, we calculated the synchronization time (τ_{syn}) for two cases: τ_{syn} is derived assuming $P_{\text{orb}} = P_{\text{rot}}$, and $\tau_{\text{syn}}(100)$ assuming $P_{\text{orb}} = 100$ days. These are given in Table 2. Depending on the individual parameters, the synchronization time can be from <100 yr up to $>10^7$ yr. This means that it is possible for a D'-type SS to be synchronized if the orbital period is short ($P_{\text{orb}} \approx P_{\text{rot}}$).

5.2 Evolutionary status of the mass donors

The mass of the mass donors in S-type SSs with known parameters are in the range $0.6 - 3.2 M_\odot$ (Mikołajewska 2003). The calculated masses of the mass donors in D'-type SSs are larger. As can be seen in Table 2, they range from 2.2 up to $6.5 M_\odot$.

Masses of $8 M_\odot$ are generally considered the upper limit for evolution to planetary nebula nuclei and white dwarfs, after heavy mass loss, especially during their AGB phases. Following our calculations for the mass of the giants (Table 2) and assuming $M_{WD} \leq 1.4 M_\odot$, the total mass of the binary is about $(M_g + M_{WD}) \sim 3.5 - 8.0 M_\odot$, in agreement with the above upper limit of $8 M_\odot$ for the WD progenitor.

The position of the mass donors on the H-R diagram is presented in Fig.2, assuming near solar chemical composition and stellar parameters as given in Sect.4.1 (see also Pereira 2005). The evolutionary tracks of Shaller et al. (1992) have been used. The donors appeared in a wide mass interval – from 2.5 to $7 M_\odot$. The derived evolutionary masses are in good agreement with those obtained from R_g and $\log g$. Three of them appeared crossing the Hertzsprung

Table 2. Parameters of D'-type SS. IR types are from the catalogue of Belczyński et al. (2000), $v \sin i$ is the rotational velocity of the mass donors (as adopted here), R_g and M_g are the radius and the mass of the giant, respectively (see Sect.4.1). τ_{syn} is the synchronization time of the binary adopting $P_{orb} = P_{rot}$, $\tau_{syn}(100)$ is the synchronization time of the binary adopting $P_{orb} = 100$ days, v_{crit} is the critical rotational velocity of the giant, P_{rot} is the rotational period of the giant, a is the semimajor axis of the system calculated supposing synchronized rotation ($P_{orb} = P_{rot}$). The values in brackets for P_{rot} and a are the upper limits, supposing 10% uncertainty in $v \sin i$ and R_g .

object	IR type	Cool Star Spectrum	$v \sin i$ [km s ⁻¹]	v_{crit} km s ⁻¹	R_g [R _⊙]	M_g M _⊙	τ_{syn} [yr]	$\tau_{syn}(100)$ [yr]	P_{rot} [days]	a [R _⊙]
HD 330036	D'	F8III	107.0	160	22.1	4.46	25	2.1.10 ⁵	<10.4 (12.8)	35(40)
Hen 3-1591	S,D'	K1III	23.7	144	23.9	3.9	8680	1.3.10 ⁵	<51.0 (62.3)	98(112)
StHα 190	D'	G4III/IV	105.0	191	7.88	2.25	27	1.3.10 ⁷	<3.78 (4.64)	15(17)
V417 Cen	D'	G9Ib-II	75.0	105	75.0	6.45	36	553	<50.6 (61.8)	112(128)
AS 201	D'	F9III	25.0	150	24.5	4.35	6423	1.1.10 ⁵	<49.5 (60.5)	99(113)

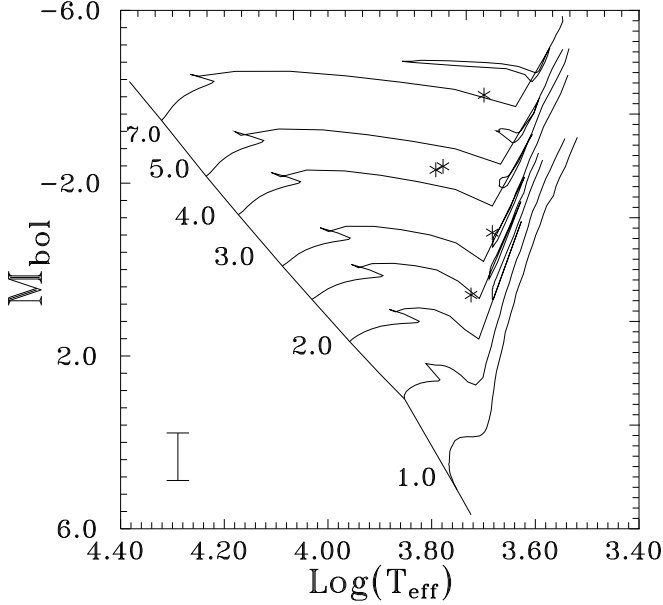


Figure 2. The position of the mass donors on the H-R diagram (see Sect.5.2). From top to bottom, the objects are V417 Cen, AS 201, HD 330036, Hen 3-1591, StHα 190. The typical error on the bolometric magnitude, M_{bol} , is plotted in the bottom left corner. The typical error on $\log T_{eff}$ is ± 0.01 .

gap (HD 330036, V417 Cen and AS 201), StHα 190 is situated near the base of the red giant branch, and Hen 3-1591 is already evolving on the red giant branch.

The relevant time for a $5M_{\odot}$ star to cross the Hertzsprung gap is $\approx 8 \times 10^5$ yr and its life time on the red giant branch is $\approx 5 \times 10^5$ yr (Iben 1991). For a $1.5M_{\odot}$ star these times are 1.5×10^8 yr and 1.57×10^8 yr (Iben 1991). These lifetimes are longer than the calculated τ_{syn} and comparable with $\tau_{syn}(100)$. This means that the rotation of the mass donors in D'-type SSs could be synchronized for these lifetimes.

5.3 Clues regarding the orbital periods

Because the orbital periods of the majority of SSs are unknown, an indirect method to obtain P_{orb} is to measure $v \sin i$. If the mass donors in SSs are co-rotating ($P_{rot} = P_{orb}$), we can find clues for the orbital periods via the simple relation $P_{orb} v_{rot} = 2\pi R_g$, where P_{orb} is the orbital period, v_{rot} and R_g are the rotational velocity and radius of the giant, respectively. It is very useful in the case of eclipsing binaries, where $\sin i \approx 1$ and $v \sin i \approx v_{rot}$. If the inclination is unknown, we can only obtain an upper limit for P_{orb} .

Using Kepler's third law [$4\pi a^3 = G(M_g + M_{WD})P^2$], we can calculate the semimajor axis of the systems. These are given in Table 2. The values in the brackets (for P_{rot} and a) correspond to the estimation of the upper limit of these parameters, assuming 10% errors in $v \sin i$ and R_g .

Up to now, from 188 SSs, the orbital elements and binary periods are well known for ~ 40 objects only (and they are all S-type). The orbital periods are in the range 200 - 2000 days (Mikołajewska 2003). As can be seen in Table 2, if D'-type SSs are synchronized, their orbital periods would be relatively short (4-60 days) and the distance between the WD and the mass donor would be 2-5 R_g .

6 DISCUSSION

The observation of fast rotation of D'-type SSs raises two further questions: first, what is the evolutionary history of these stars which has produced such high rotation, and second, what does the effect of high rotation have on their mass loss and subsequent dust formation?

We see three possible reasons for the fast rotation of mass donors in D'-type SSs:

(i) the rotation is synchronized with the binary period ($P_{rot} = P_{orb}$). In this case their orbital periods should be short $\lesssim 50$ days.

However, it also could be, that they are not synchronously rotating. The possibility that $P_{rot} > P_{orb}$ has to be excluded because the orbital separations would be unreasonably small, and the synchronization time would be extremely short (they will be synchronized in 30-9000 years; see τ_{syn} in Table 2). If $P_{rot} < P_{orb}$, reasons for their fast rotation could be:

(ii) the current giants have been spun-up from the transfer of angular momentum. Jeffries & Stevens (1996) proposed a mechanism in which accretion of a slow massive wind from the AGB progenitor of the current white dwarf can transfer sufficient angular momentum. This also explains the chemical enrichment in s-process elements in D' SSs, that were present in the AGB wind (see also Pereira et al. 2005). Mass transfer via L₁, when the current white dwarf was the mass donor, can also spin-up the companion, as in millisecond radio pulsars (van den Heuvel 1984).

(iii) planet swallowing to spin up the giant. Rough estimation gives angular momentum transfer during a collision of a planet with mass m_p and velocity v_p to a giant of mass M_g , of the order of $\Delta\Gamma = m_p v_p R_g$. This causes a change in the giant's rotational velocity $\Delta v_g^{rot} = m_p v_p / \text{const.} M_g$, where $\text{const.} = J_g / M_g R_g^2$ depends on the internal structure of the giant. ($\text{const.} = 0.4$ for a solid uniform density sphere, and less for a star-like centrally condensed sphere). Assuming a centrally condensed star (giant) such that $\text{const.} = 0.01$, $v_p = \sqrt{GM_g/R} \sim 10 - 100 \text{ km s}^{-1}$, $M_g = 2 - 10 M_\odot$ and $m_p = 0.01 M_\odot$ we estimate $\Delta v_g^{rot} \sim 1 - 50 \text{ km s}^{-1}$, showing that in the right circumstances, the planet could spin up the giant to the rotational velocities observed in D'-type SSs.

Fast rotation, i.e. $v_{rot} \geq 0.5 v_{crit}$, may change a spherical star with a spherical wind into an equatorially flattened system, with both the radius of the star and stellar wind parameters depending on the stellar latitude. Such stars will have an equatorial radius significantly larger than the polar one, and equatorially enhanced mass loss (see Lamers 2004 and references therein).

Because it seems that the majority of the giants in D'-type SSs are rapid rotators (Sect. 4.3), we expect that:

- (1) they have a larger mass loss rate than the slower rotating giants;
- (2) their mass loss is enhanced in the equatorial regions;
- (3) they could be even equatorially flattened.

It is possible, that the dusty environment in D'-type SSs is connected with rapid rotation of the mass donors. Intense mass loss in the equatorial regions can lead to the formation of an excretion disc in which the higher gas density enhances dust formation and growth. The broad IR excess in D'-type SSs can be due to the temperature stratification in the dust from such an excretion disc (Van Winckel et al. 1994). Other possible explanations for the presence of dust can be that it is left over from the formation of a planetary system, or it is a relic from a strong dusty mass loss when the present day white dwarf was on the AGB. However, we consider it is more likely that it originates in the current outflow and that this is enhanced in the equatorial regions by rapid rotation.

7 CONCLUSIONS

Our main results are:

- (1) We have measured the rotational velocities of the mass donors in D'-type symbiotic stars, using the CCF approach.
- (2) Four of the five objects appeared to be very fast rotators compared with the catalogues of $v \sin i$ for the cor-

responding spectral types. At least three of them rotate at a substantial fraction ($\gtrsim 0.5$) of the critical velocity. This means that at least in D'-type SSs, the cool components rotate faster than isolated giants (as predicted by Soker 2002).

(3) If they are tidally locked, the orbital periods should be as short as $\lesssim 10$ -50 days.

(4) As a result of the rapid rotation, they must have larger mass loss rates than the more slowly rotating giants, and their mass loss is probably enhanced in the equatorial regions.

To understand better these objects, we need their binary periods to be derived from radial velocity measurements and the inclination determined. In subsequent papers, we plan to explore the projected rotational velocity of the cool giants in the other types of symbiotic stars and to compare their rotational velocities with that of the isolated giants with similar mass and evolutionary stage.

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